2.2 Robotic Surface Power

Capabilities	Mission or Road Map Enabled	State of Practice	Minimum Estimated Development Time (years)
Low temp. battery -40 to -80C MMRTG and SRG Milliwatt/multi-watt RPS Advanced 100 We class RPS Mars Durable Array 200 W/kg	Lunar rovers, MSL1, MSL2, Mars Scouts, MHP1, MSR, Astrobiology Foundation Lab, MSHP, New Frontiers, Europa lander, Titan lander	Energy Storage: -20 C Radioisotope: None Nuclear Fission: None Solar: 40-60 W/kg	Low temp. batt: 4 (-40 C), 17 (-80 C) MMRTG and SRG: Currently in development. Flight units available in 2009 Milliwatt/Multiwatt RPS: 4 Advanced RPS: 6 Mars Durable Array: 13

2.3 Human Surface Power

Capabilities	Mission or Road Map Enabled	State of Practice	Minimum Estimated Development Time (years)
Long life batt 160 - 200 Wh/kg, Primary batt 400 - 600 W/kg, Fuel cells 400 - 600 W/kg, Regen fuel cells 400 - 600 Wh/kg, Lunar solar array >150 W/kg, Advanced 100 We class RPS, Multi-kWe class RPS Lunar surface fission power system Mars durable PV array 200 W/kg, Mars surface fission power system)	Lunar Sortie Missions (Power for human lunar expeditions, astronaut suit power, science package & rover power) Single Location Lunar Outpost (Astronaut suit power, rover power, lunar habitat power, high power for ISRU), Human Mars Exploration (Mars Surface Power)	Solar: None Nuclear Fission: None Radioisotope: None Energy Storage: None	Long life batt: 11 (160 Wh/kg), 19 (200 Wh/kg) Primary batt: 8 (400 W/kg), 13 (600 W/kg) Fuel Cells: 7 (400 W/kg), 13 (600 W/kg) Regen Fuel Cells: 7 (400 Wh/kg), 20 (600 Wh/kg) Lunar solar array: 8 Advanced RPS: 6 Multi-kWe RPS: 8 Lunar surface fission power: 13 – Mars durable solar array: 13 Mars surface fission power system: 13

2.4 Science and Robotic Spacecraft Power

Capabilities	Mission or Road Map Enabled	State of Practice	Minimum Estimated Development Time (years)
Long life batt 100 - 200 Wh/kg, flywheels 100 - 200 Wh/kg MMRTG and SRG, Solar Array 200 - 300 W/kg, Prim batt 400 - 600 W/kg, milliwatt /multiwatt RPS, Advanced RPS, Kilowatt class RPS)	Mars Telecon Orbiter, Europa Orbiter, Neptune orbiter	Solar: 40-60 W/kg Nuclear Fission: None Radiosotope: GPHS RTG 5.3 We/kg, 6.6% eff. Energy Storage: Li batteries 90 Wh/kg	Long life batt: 3 (100 Wh/kg), 19 (200 Wh/kg) Flywheels: 4 (100 Wh/kg), 12 (200 Wh/kg) MMRTG and SRG: Currently in development. Flight units available in 2009. Solar array: 5 (200 W/kg), 8 (300 W/kg) Prim batt : 8 (400 W/kg), 13 (600 W/kg) Milliwatt/multiwatt RPS: 4 Advanced RPS: 6 Kilowatt class RPS: 6

2.5 CEV Power

Capabilities	Mission or Road Map Enabled	State of Practice	Minimum Estimated Development Time (years)
200 Wh/kg 5000 hour primary fuel cells 120 Wh/kg, long life Li polymer batteries 200 W/kg solar array	First Crewed CEV Flight	Solar: ISS arrays Energy Storage: Shuttle Fuel Cells 90 WH/kg, 2600 hrs	Primary Fuel cells: 3 Long life Li polymer batteries: 3 Solar array: 5

2.6 Robotic Planetary Propulsion

Capabilities	Mission or Road Map Enabled	State of Practice	Minimum Estimated Development Time (years)
100-200 kWe class NEP Prometheus 1, sub-kilowatt EP for REP	JIMO, Neptune Orbiter, Interstellar Probe, Pluto Orbiter, Saturn Moon Tours, Neptune Moon recon, Trojan Asteroid Rendezvous	Chem: Solid or storable propellants NEP:None REP: None	100-200 kWe class NEP: 10 Sub-kilowatt EP for REP: 8

2.7 Human Exploration Propulsion

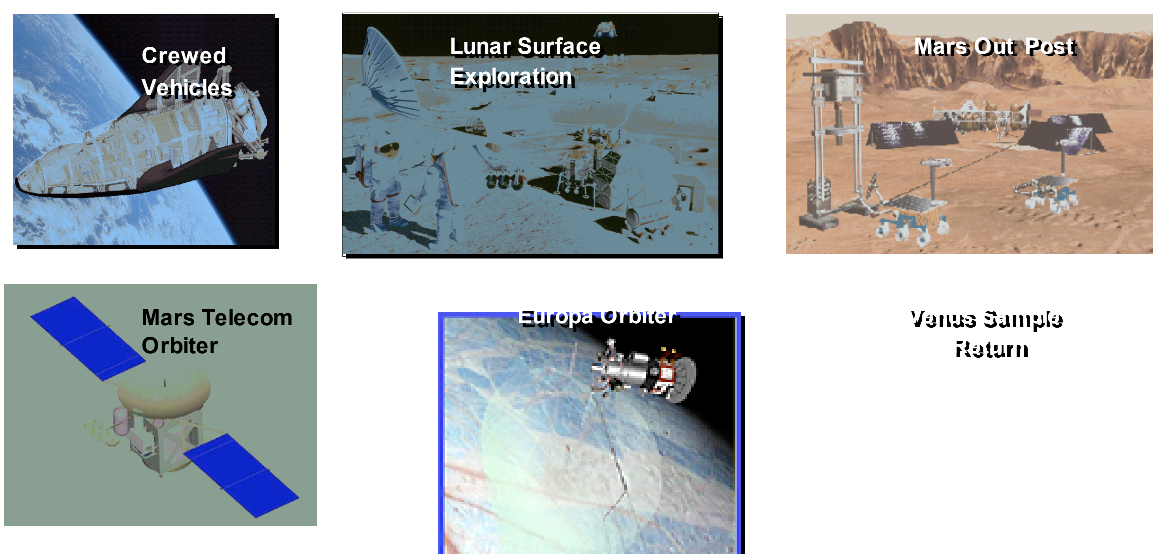
Capabilities	Mission or Road Map Enabled	State of Practice	Minimum Estimated Development Time (years)
200-500 kWe SEP lunar cargo vehicle, MWe SEP lunar cargo vehicle, single engine (B)NTP lunar cargo vehicle, MWe SEP Mars piloted vehicle, 5 MWe NEP Mars cargo vehicle, 15 MWe NEP Mars piloted vehicle, Multiple engine (B)NTP Mars cargo vehicles, single and multiple engine (B)NTP piloted vehicles	Lunar and Mars human exploration missions (lunar cargo vehicles, Mars cargo and piloted vehicles)	Chem:none SEP: None NEP:None NTP: None	200-500 kWe SEP lunar cargo vehicle: 12 MWe SEP lunar cargo vehicle: 18 Single engine (B)NTP lunar cargo vehicle: 15 SEP Mars piloted vehicle:20 5 MWe NEP Mars cargo vehicle: 20 15 MWe NEP Mars piloted vehicle: 23 Multiple engine (B)NTP Mars cargo vehicles: 20 Single and multiple engine (B)NTP piloted vehicles: 18 and 23 respectively

2.8 Relationship to Other Roadmaps

The High Energy Power and Propulsion roadmap is critically linked to the following other Roadmaps:

- Robotic access to planetary surfaces roadmap where power is required to operate scientific instruments and to provide power to rovers. In addition, advanced propulsion systems and the power sources needed to power them are required for the exploration of distant destinations.
- Human Health and Support Systems Roadmap because of the need for reliable power in considerable quantity to maintain a viable local environment for humans and to provide the energy humans need to perform their activities.
- Human Exploration Systems and Mobility roadmap because of the need to provide power for mobility vehicles to be used during human exploration.
- In situ Resource Utilization roadmap which has as an objective the recovery of local resources that enable continued and extended exploration. Resource recovery is an energy intensive process and nuclear power is an excellent or even necessary way to provide this power.

Future Space Applications of Energy Storage Systems



2.9 Infrastructure Assessment

2.9.1 Nuclear Fission Systems

Facility	Exists?	Comment
Ground prototype testing	no	Reactor test facilities in vacuum/environment chambers (possibly with cold walls)
Fuel fabrication process development labs and fuel fabrication facilities	Limited (DOE & Industry)	DOE has some fabrication capability for UN and coated-particle carbide fuels Industry has fabrication capability for low- and high-enriched UO2 fuels with Zr cladding No fabrication capability exists for NTP composite or cermet fuels
Fuel and Material Irradiation	Limited (DOE and Universities)	Thermal-spectrum irradiation capabilities exist within DOE and academia No fast-spectrum irradiation capabilities exist in U.S. No facilities exist for prototypic NTP fuel irradiation
Fuels & Material Post Irradiation Evaluation (PIE)	Yes (DOE)	DOE (INL and ORNL) has comprehensive PIE facilities that could be augmented to meet all envisioned testing requirements
Thermal-hydraulic test loops	no	Variety of loops required for code and design validation, component and sub-system testing.
I&C test beds	no	Validates instrumentation and control system design
Power conversion and heat rejection system testing	Limited (NASA, DOE, Industry)	Facilities required for stand-alone component testing and for testing of the PCS and HRS as an integrated component of electrically-heated Engineering Development Units (EDUs).
Safety Testing	Generally, no	Facilities for fuel ablation testing, over-power testing, fission product release testing, hydrodynamic impact testing, etc. will be required
Physics Critical	Limited – DOE	TA-18 facility @ LANL is being relocated to NTS and availability dates are unclear Re-commissioning of ZPPR facility @ INL is possible

* Note: There is some potential synergism between surface power test facility requirements and those for low-power NEP. Thus, dual-use facilities may be possible in several instances. However due to differences in temperatures, materials, coolants, fission energy spectrum, technologies, etc., there is very limited synergism between surface power, NTP, and MMW-NEP test facility functional requirements. Dedicated facilities would be required in most cases for these concepts.

2.9.2 Nuclear Thermal Propulsion

Facility	Exists?	Comment
Hot hydrogen test facility	no	Needed for both un-irradiated and irradiated fuels and materials
NTP Engine test facility	no	
Nuclear furnace	no	May be required – particularly if non-NERVA-heritage fuel is employed

3 Roadmap Development Process

3.1 Roadmap Development

The team formed four sub-teams centered around the key technical areas: solar, energy storage, radioisotope, and fission. The overall team developed strawman requirements and assumptions, in consultation with the other roadmap teams. The sub-teams then developed their initial "independent" Capability Roadmaps based on these strawman requirements and assumptions, current state-of-technologies and projected trajectories of advancing technologies. The sub-team roadmaps were then "rolled up" into the overall High Energy Power & Propulsion roadmap in an iterative process. The final product represents a consensus opinion of the High Energy Power & Propulsion team members, but is not the official view of NASA or DOE. A summary of the final Roadmap was presented to the National Research Council in April 2005.

3.1.1 Capability Breakdown Structure

Figure 2.1 shows the Capability Breakdown Structure (CBS) for the High Energy Power & Propulsion (HEP & P) Roadmap activity. Each of the major items identified across the top represent a major power or propulsion human exploration or science capability to be satisfied. Those items are Robotic Surface Power (2.1), Human Exploration Surface Power (2.2), Science & Robotic Spacecraft Power (2.3), CEV Power (2.4), Robotic Planetary Propulsion (2.5), and Human Exploration Propulsion (2.6). The sub-capabilities below these major capabilities represent potential system capabilities that could satisfy the major capabilities. As described earlier, the HEP & P sub-teams were organized to represent the sub-capabilities to meet the major capabilities. Converters, power management and distribution, heat rejection, and materials were shown to support all capabilities.